Dust motion in the divertor sheath

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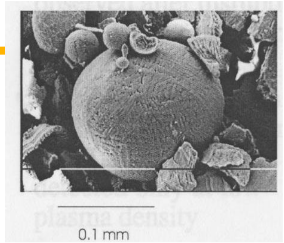
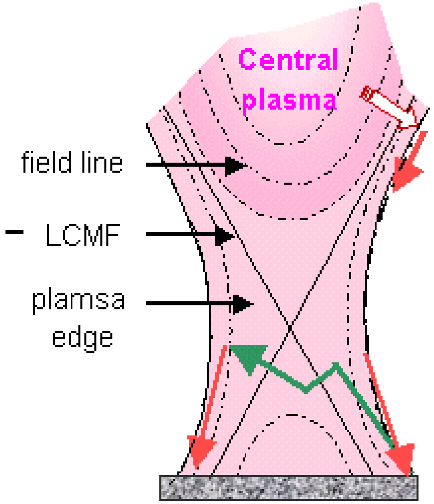
Outline

- Motivation: ITER
- The physics of dust in fusion devices
- The divertor sheath
- Dust dynamics
- Conclusions

Existing tokamaks produce dust



- Presence of dust (UFOs) known for a long time
- Produced by plasma-material interaction, maintenance
- Not an issue in short-pulse tokamaks: lower heat load $q_{ref} = 1\,\mathrm{MW/m^2}$
- A problem in ITER-era: higher heat load $q_{ref} = 10\,\mathrm{MW/m^2}$
  - hundreds kgs of dust estimated for ITER
- Safety issues:
  - Beryllium: toxicity, chemical reactivity
  - Carbon: tritium retention
  - Tungsten: radiotoxicity
- Operational issues:
  - PMI. Dust survivability. Non-local redeposition
  - Dust penetration. Plasma pollution, disruptions



Axisymmetric divertor

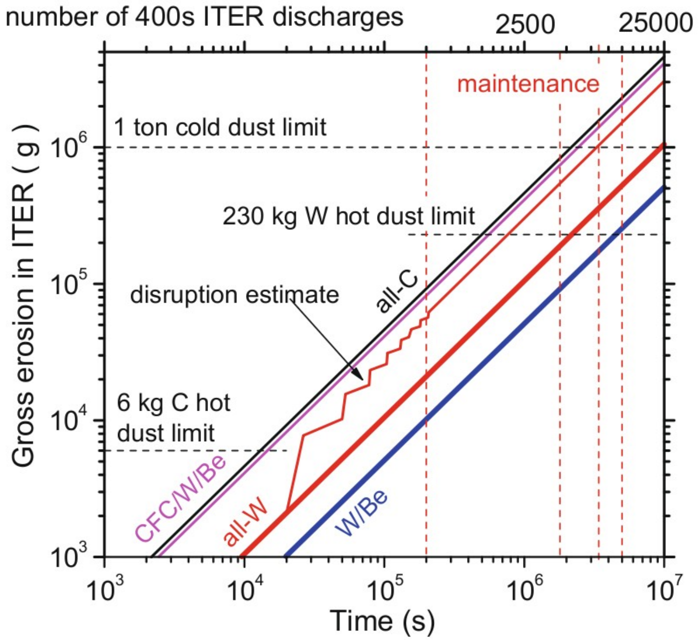
Dust in the ITER-era

- ITER dust safety limits
- Based on engineering estrapolations
- Limit can be reached before manteinance

Table 1
Safety and administrative limits for tritium and dust in vessel inventories taken into account in this study.

	Safety limits	Administrative limit
In vessel T inventory	1 kg	700 g
Global in vessel dust inventory	1 ton	670 kg
Dust on hot surfaces	6 kg of C, 6 kg of W, 6 kg of Be If no C present, 11 kg for Be, and 230 kg for W*	No assessment available

* ITER Organisation has recently (2009) reduced this limit to 77 kg W.



Roth et al., J. Nucl. Mat (2009)

What is the physics base
to support these estrapolations?

Dust survivability is the focus:
can we really have that many kgs?

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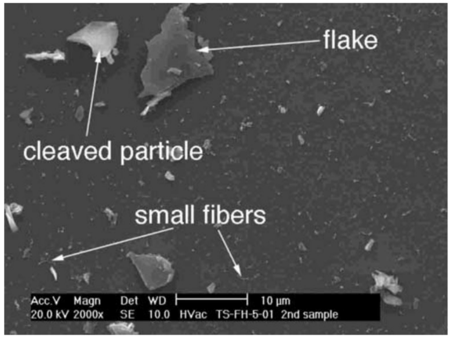
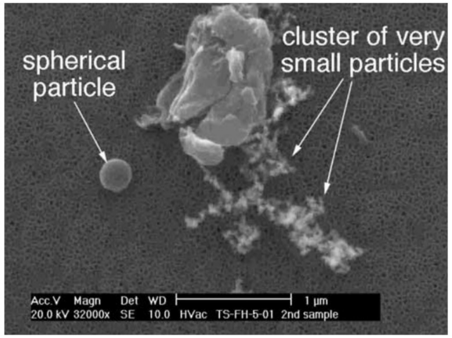
Key questions for dust in fusion devices

- How is dust generated? We do not know!
  - 10-15% of eroded wall material
  - Size distribution and birth rate: micrometer dust?
  - Tungsten?



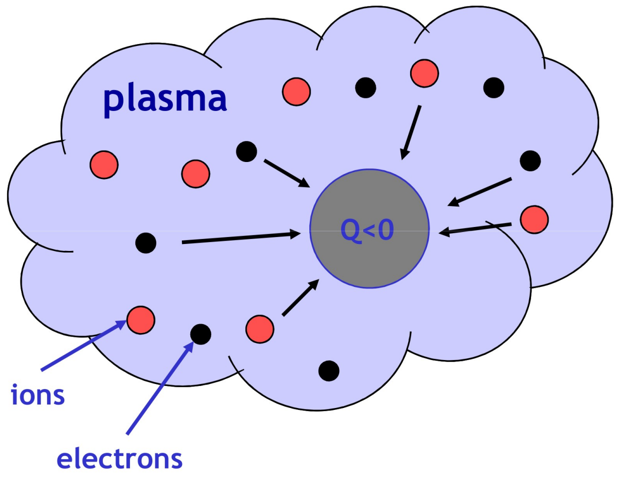


Sharpe et al. Fus. Eng.Des (2002)

- How is dust transported? Can dust survive?
  - Addressed in this talk
  - Conclusion: 1 MW/m^2 heat load qualitatively different relative to 10 MW/m^2

What is the physics of dust transport?

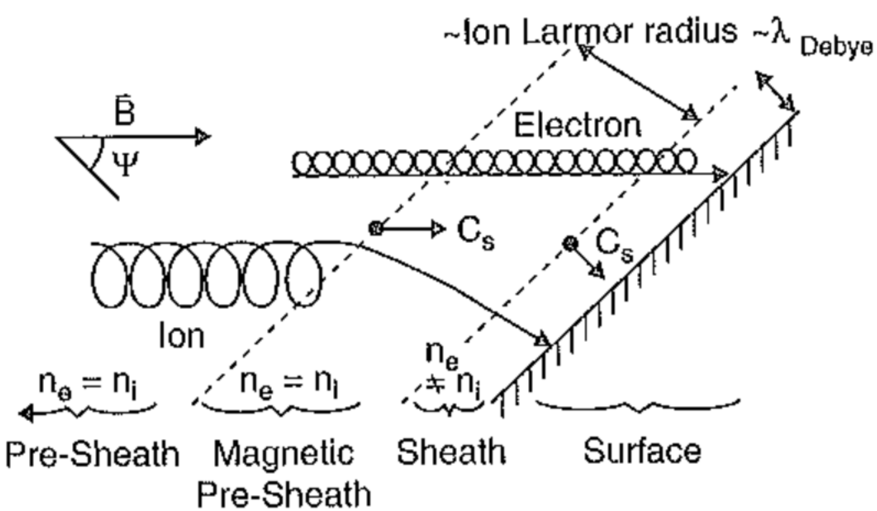
- Dust charging: $$\frac{dQ_d}{dt} = I_i + I_e + I_{se} + I_{th}$$
- Dust motion: $$\frac{d\mathbf{r}}{dt} = \mathbf{V}_d$$ $$m_d \frac{d\mathbf{V}_d}{dt} = Q_d \mathbf{E} + \mathbf{F}_{id}$$
- Dust grain heating: $$m_d C_d \frac{dT_d}{dt} = q_e + q_i - q_{se} - q_{th} - q_{rad}$$



- Coupled with the background plasma model
- Currents, ion drag and heat fluxes modeled by the OML theory
- Standard model, also used by other groups:
  - DUSTT: Krasheninnikov and collaborators in the US
  - DTOKS: Coppins and collaborators in UK

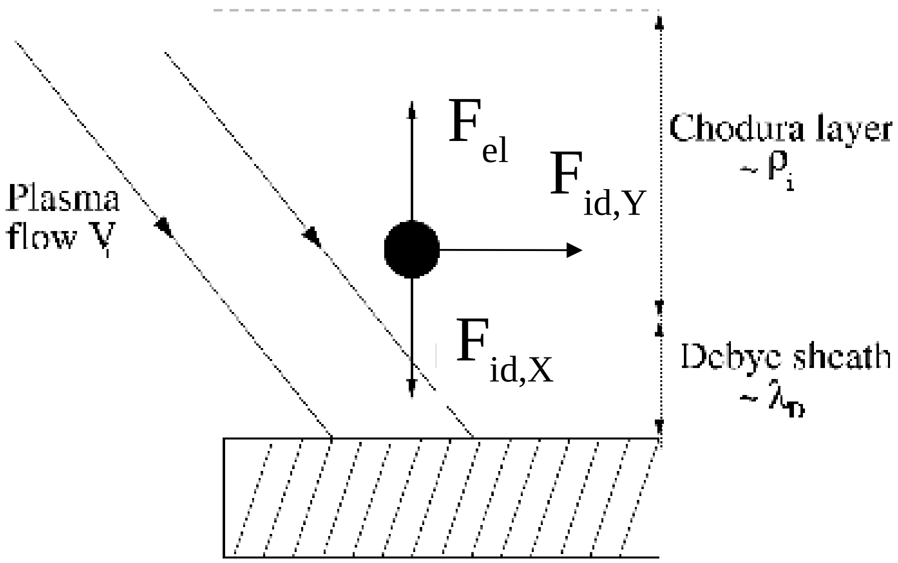
Background plasma model: divertor sheath

- Focus on the divertor (larger heat load)
- The magnetized sheath: Chodura's picture (wall negatively charged)
  - Debye sheath, nonneutral, $\sim\lambda_D$
  - Chodura layer, quasineutral, $\sim\rho_i$
  - Presheath, quasi-neutral

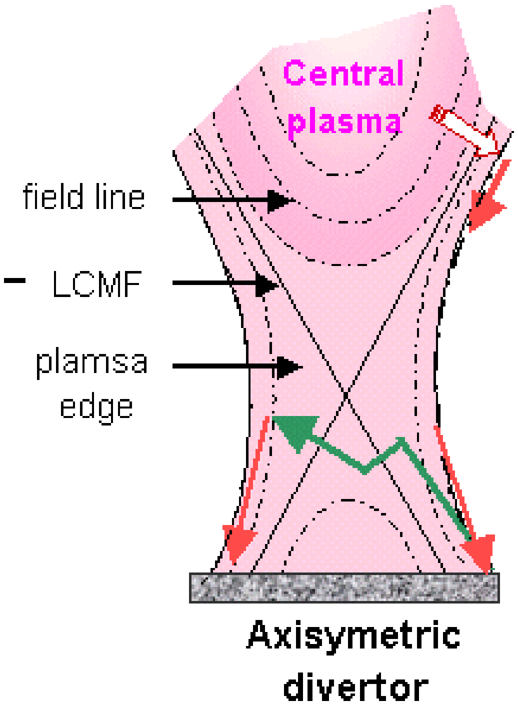


Dust motion in the sheath

Vertical: force balance, levitation, oscillation around equilibrium
Poloidal and toroidal: unbalanced, strong acceleration



Tomita's poster yesterday

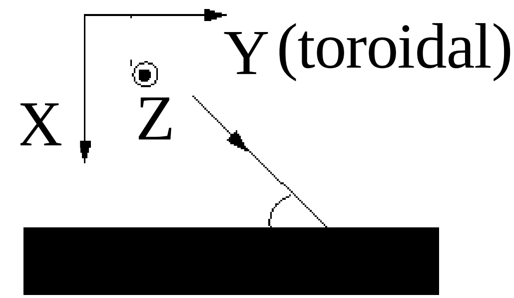


Poloidal injection impacts for survivability!

Bragisnkii modeling of the sheath

- Magnetized limit, no stress-tensor, steady-state, 1D

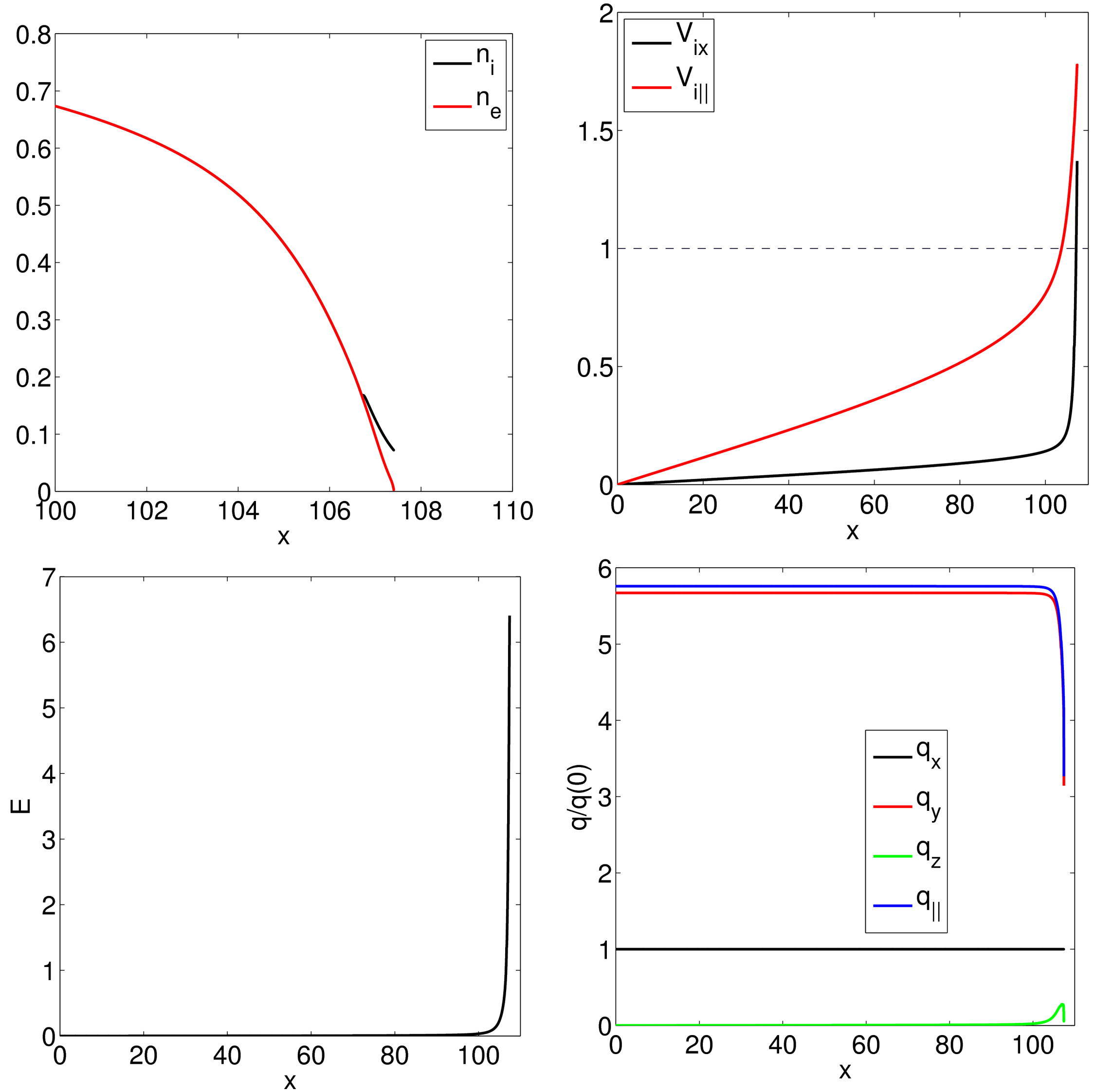
$$
\begin{aligned}
&\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{V}_e) = \nu_i n_e \\
&\frac{\partial}{\partial t}(m_e n_e \mathbf{V}_e) + \nabla \cdot (m_e n_e \mathbf{V}_e \mathbf{V}_e) = -\nabla (n_e T_e) - e n_e \left(-\nabla \phi + \mathbf{V}_e \times \mathbf{B}\right) + \mathbf{R} \\
&\frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e + n_e \frac{m_e \mathbf{V}_e^2}{2}\right) + \nabla \cdot \left(\mathbf{q}_e + \frac{5}{2} n_e T_e \mathbf{V}_e + n_e \frac{m_e \mathbf{V}_e^2}{2} \mathbf{V}_e\right) = Q_e + e n_e \nabla \phi \cdot \mathbf{V}_e + \mathbf{R} \cdot \mathbf{V}_e \\
&\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_i) = \nu_i n_e \\
&\frac{\partial}{\partial t}(m_i n_i \mathbf{V}_i) + \nabla \cdot (m_i n_i \mathbf{V}_i \mathbf{V}_i) = -\nabla (n_i T_i) + e n_i \left(-\nabla \phi + \mathbf{V}_i \times \mathbf{B}\right) - \mathbf{R} \\
&\frac{\partial}{\partial t}\left(\frac{3}{2} n_i T_i + n_i \frac{m_i \mathbf{V}_i^2}{2}\right) + \nabla \cdot \left(\mathbf{q}_i + \frac{5}{2} n_i T_i \mathbf{V}_i + n_i \frac{m_i \mathbf{V}_i^2}{2} \mathbf{V}_i\right) = Q_i - e n_i \nabla \phi \cdot \mathbf{V}_i - \mathbf{R} \cdot \mathbf{V}_i \\
&\nabla^2 \phi = \frac{e}{\varepsilon_0}(n_e - n_i)
\end{aligned}
$$



- Uniform, static population of neutrals
- Conservation of energy flux: $\nabla \cdot \left(\mathbf{q}_e + \mathbf{q}_e^{conv} + \mathbf{q}_i + \mathbf{q}_i^{conv}\right) = 0$
- Equations integrated from upstream to the wall
  - Upstream: zero particle flux, conductive heat flux

Braginskii sheath profiles

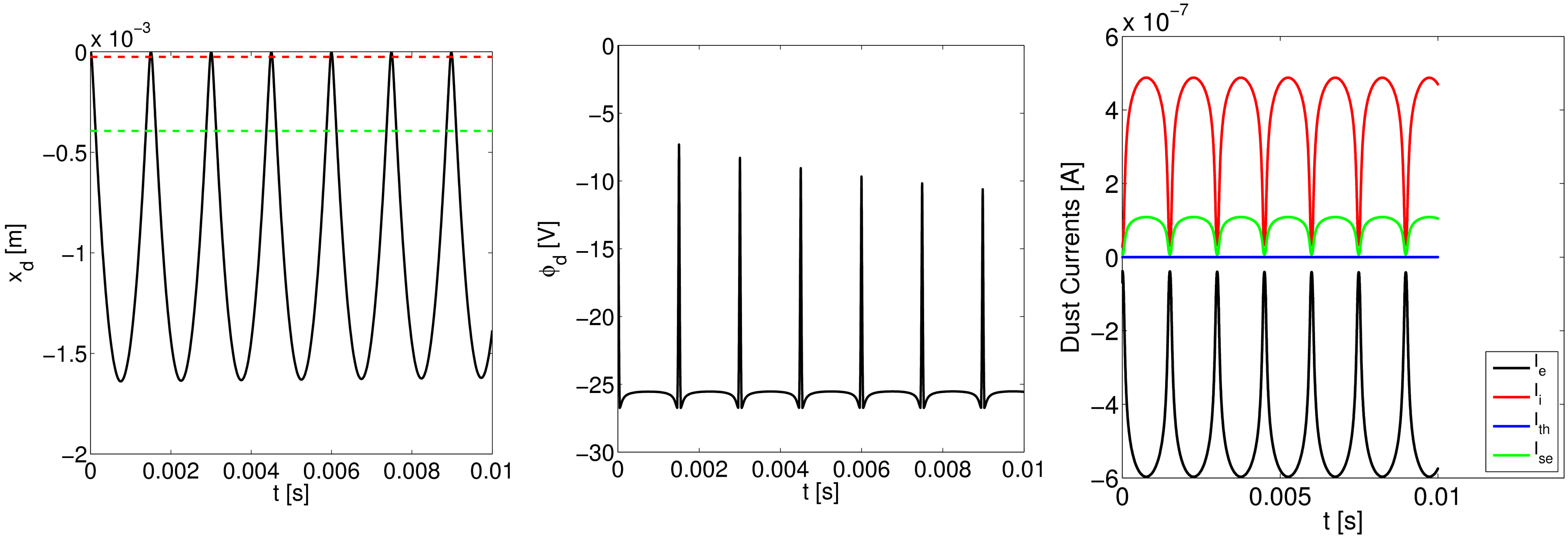
$\theta = 10^\circ$



Dust must stay close to the wall to survive!

1 μm dust particle sheath dynamics in 1 MW/m²

- Carbon dust. Released at the wall with no injection velocity
- Bounces back and forth in the sheath-presheath



Tungsten dust qualitatively similar

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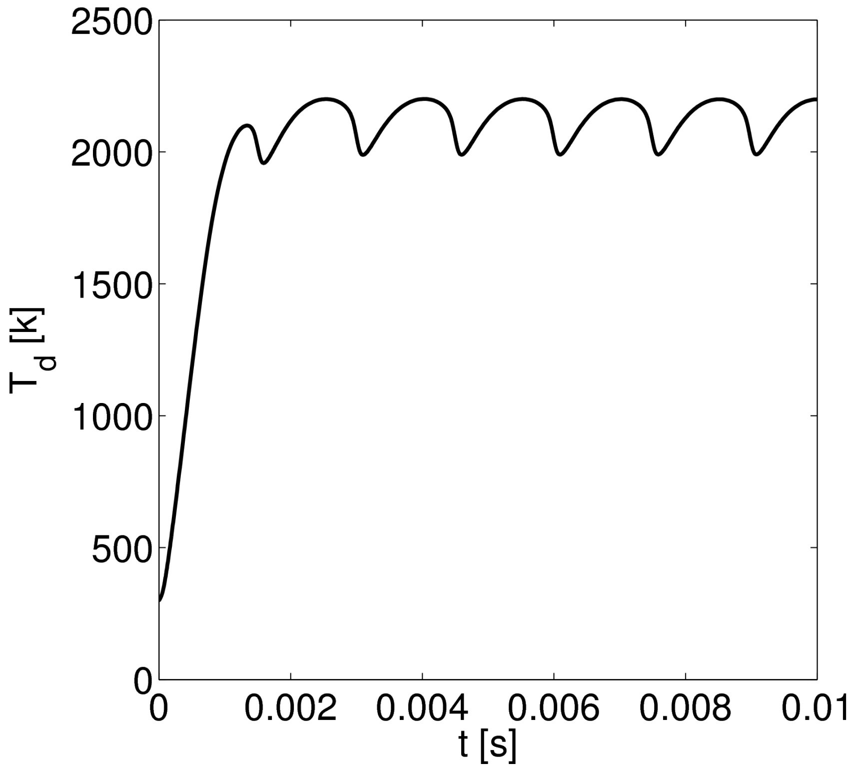
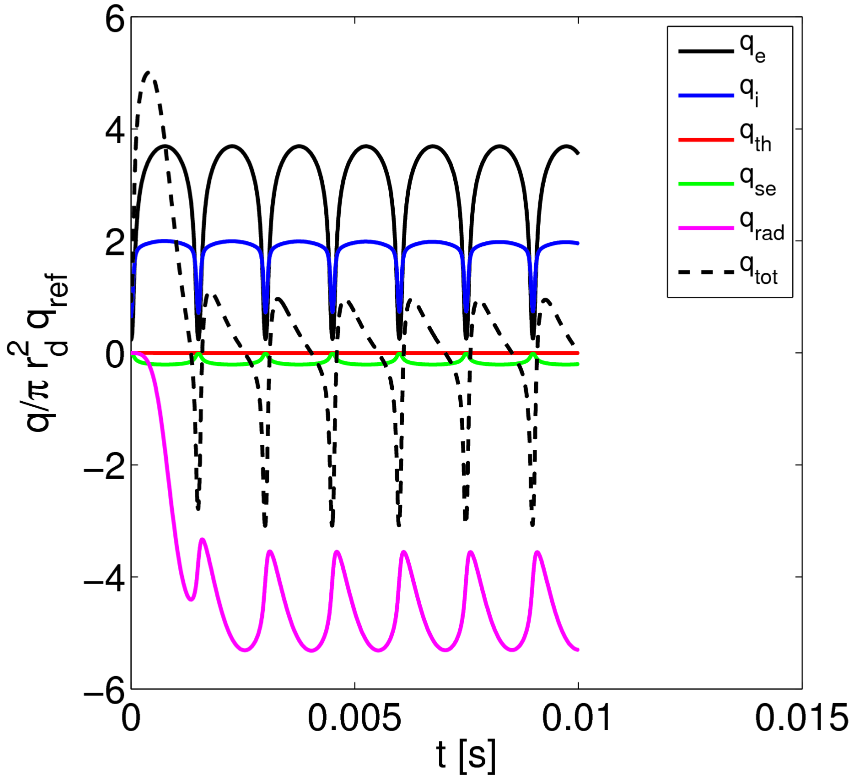
1 µm dust particles can survive in 1 MW/m²

- The dust temperature does not reach melting conditions
- The radiative flux is key to cool the dust!

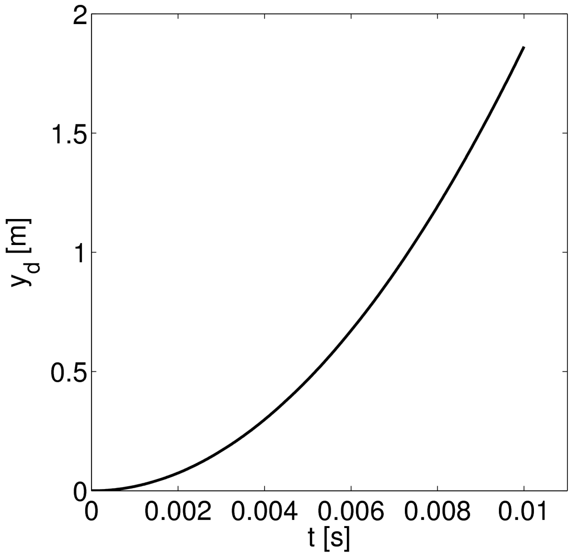




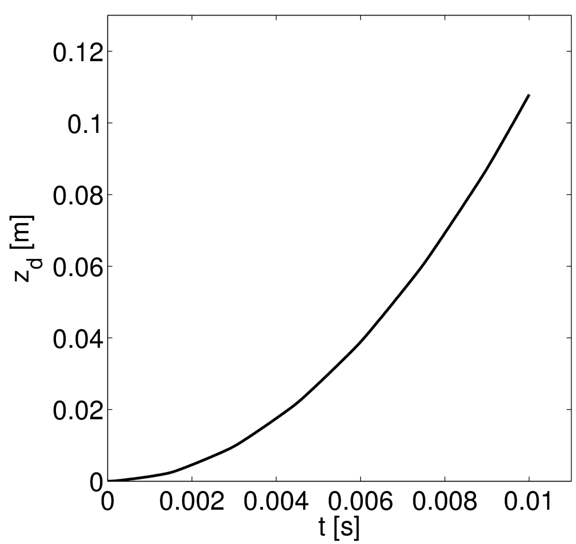
1 µm dust particles can survive in 1 MW/m²

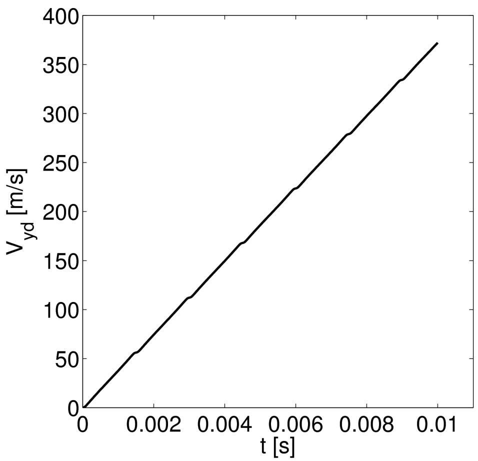
- Accelerated to high speed, travel long distances
- Surface inhomogeneity can redirect it towards the core (Krasheninnikov et al, PoP 04)

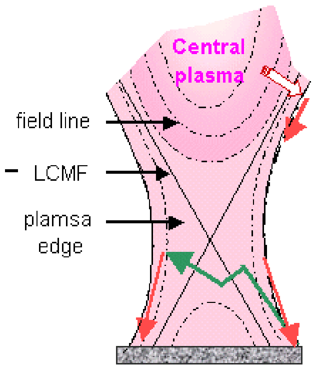
Toroidal transit distance



Poloidal transit distance



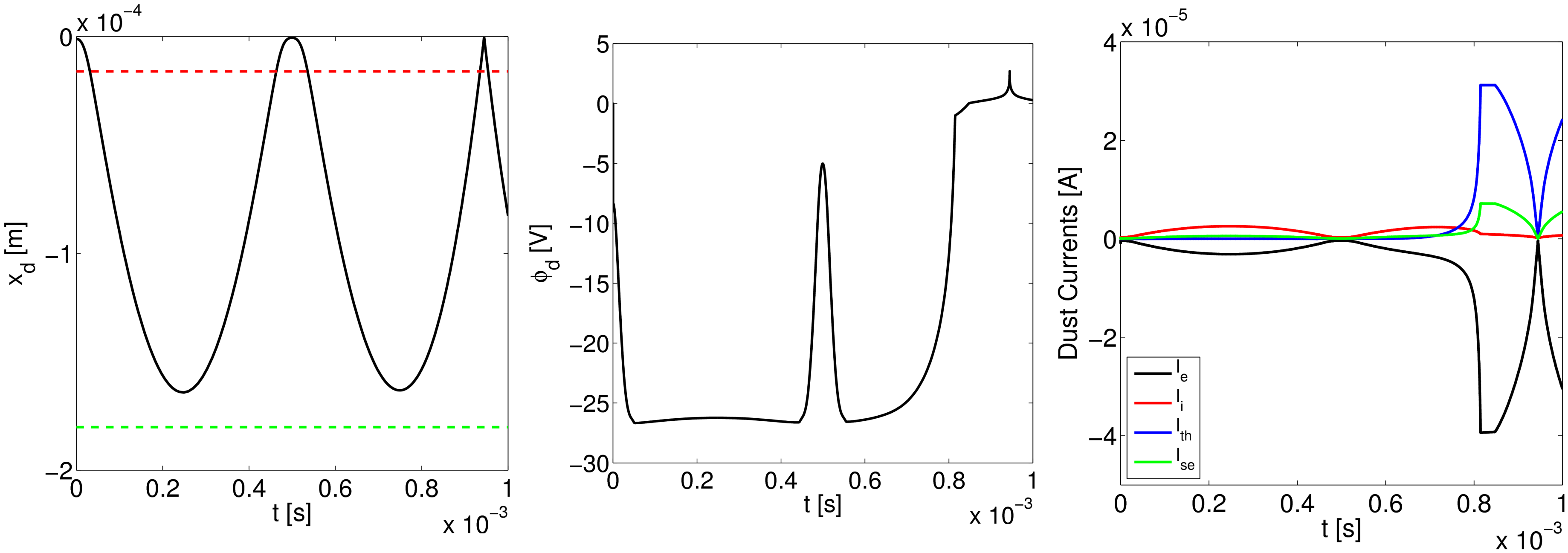




Axisymetric divertor

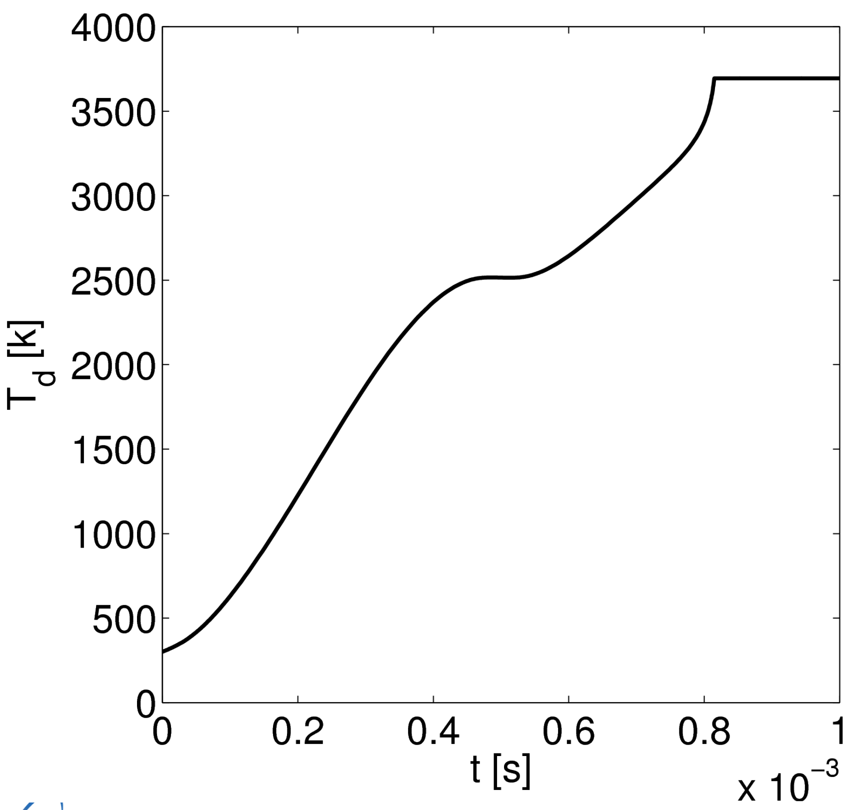
1 µm dust particle sheath dynamics in 10 MW/m²

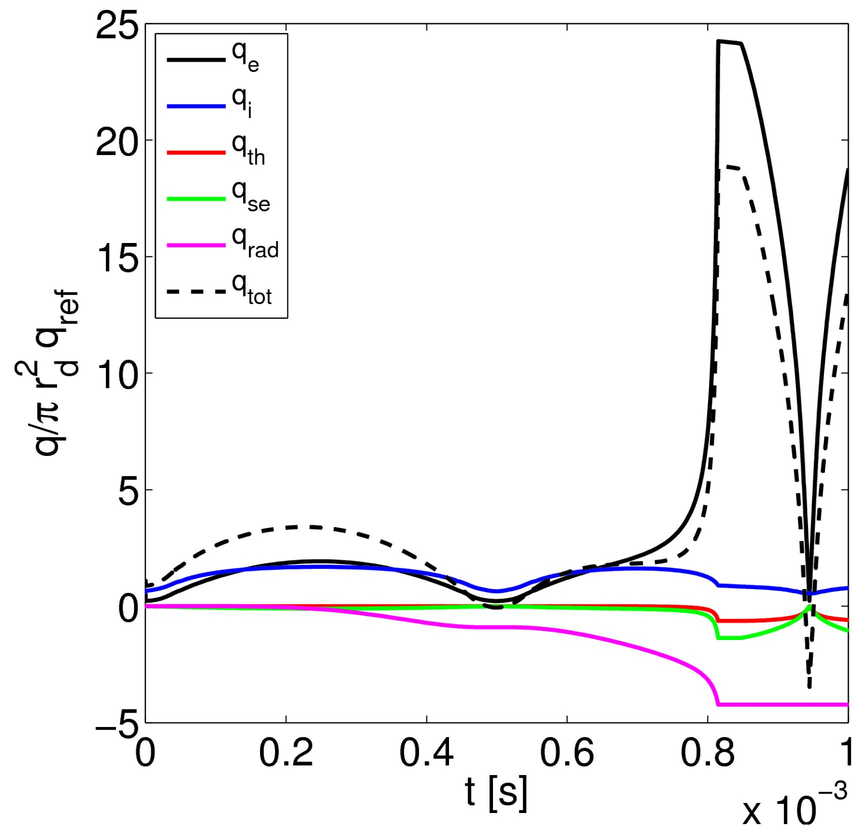
- Tungsten dust ($T_{melt} \simeq 3700$ K)
- Shorter duration, fewer collisions with the wall before melting
- Dynamics: symmetry is broken by the equation of state



1 µm dust survivability drastically reduced in 10 MW/m²

- Dust reaches melting condition quickly!
- Thermionic emission induces heat flux collection spike

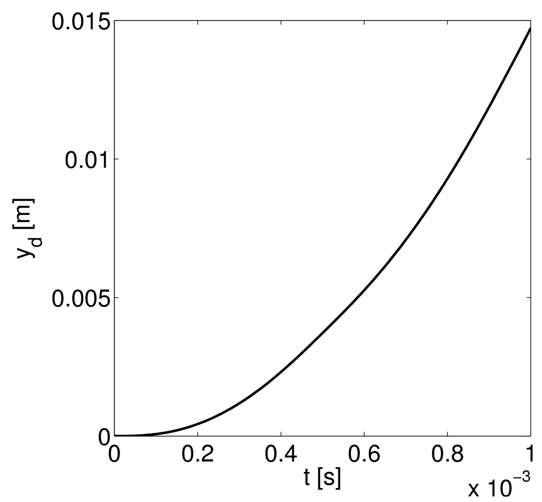




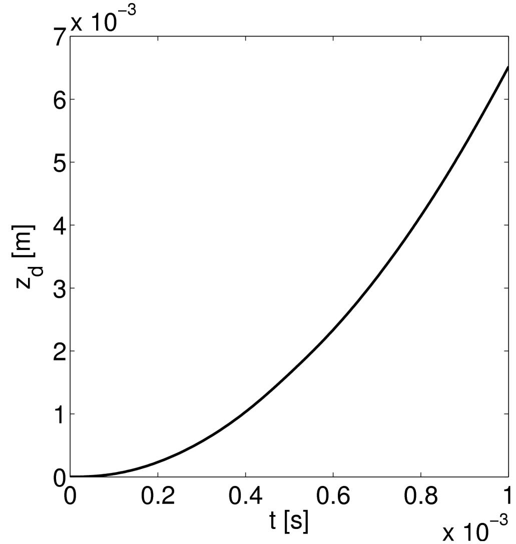
1 µm dust redeposits non-locally in 10 MW/m^2

- Does not move much. Reduced probability to be redirected towards the core

Toroidal transit distance

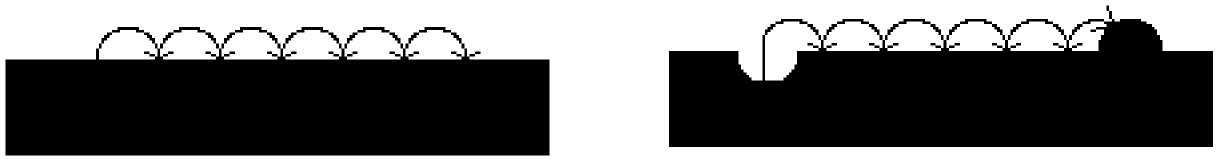


Poloidal transit distance

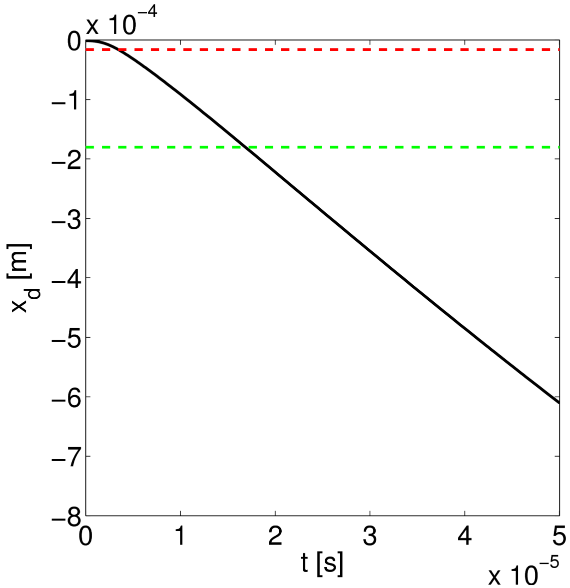


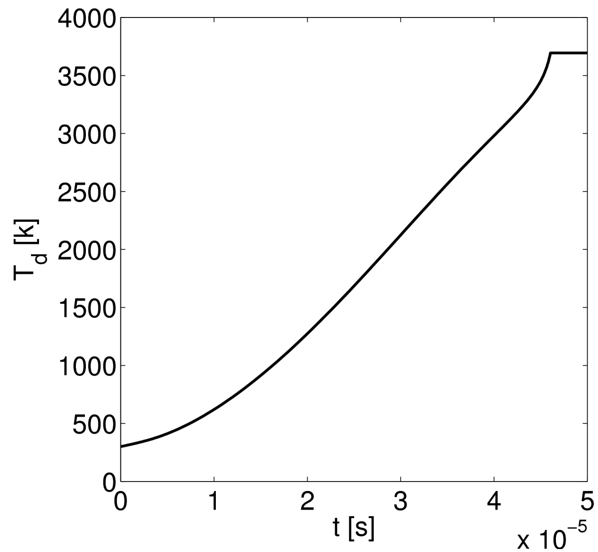
Critical poloidal injection speed to transit divertor w/o melting: L/τ_{melt}~370 m/s

- Redeposits non-locally. Fixed plasma poloidal flow direction leads to mass migration

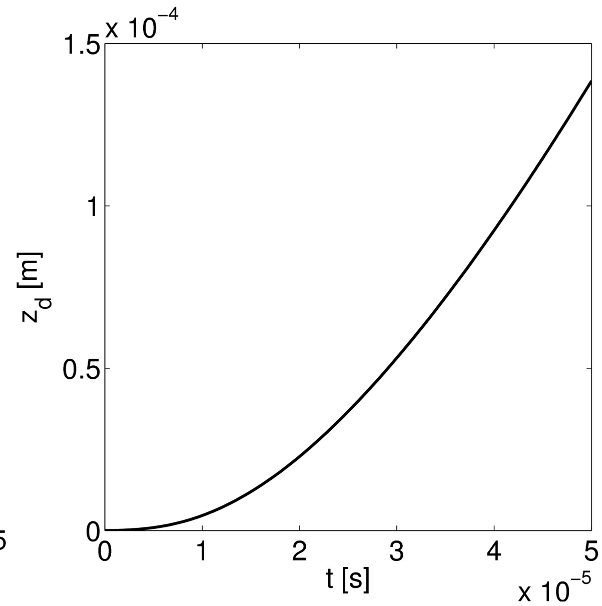


0.1 μm dust particles in 10 MW/m²: redeposits locally!





Poloidal transit distance



$F_{el} \sim r_d$

$F_{drag} \sim r_d^{\,2}$

Critical poloidal injection speed to transit divertor w/o melting:

$L/\tau_{melt} \sim 6500$ m/s

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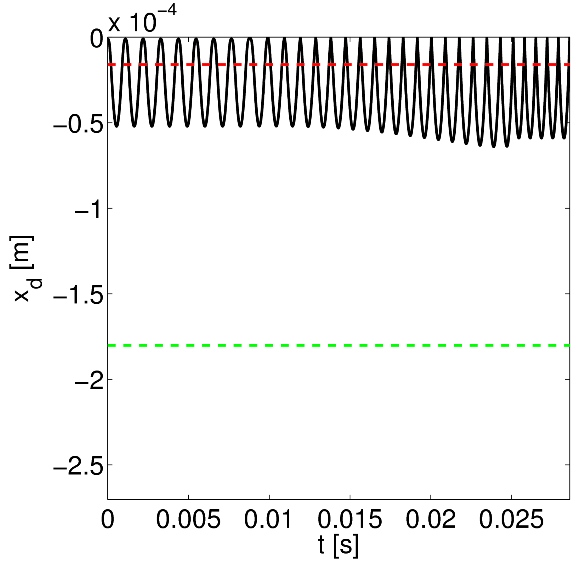
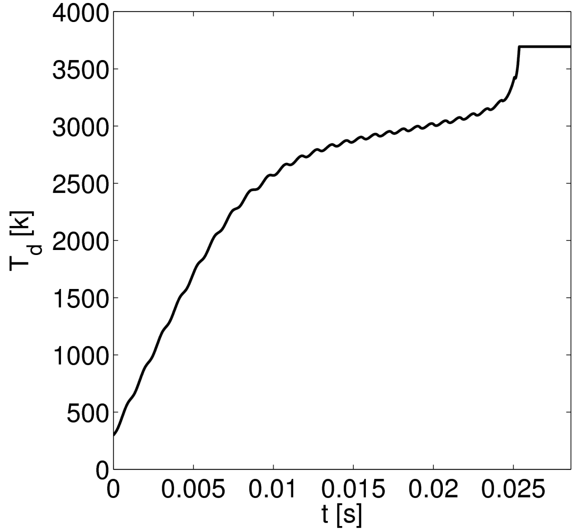
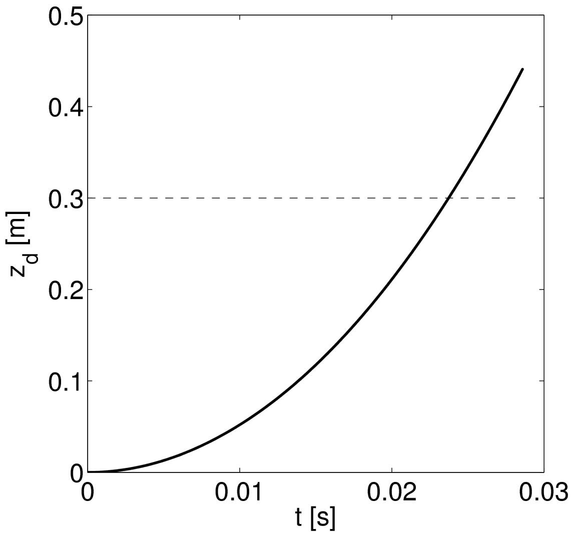
10 μm dust particles in 10 MW/m²: can survive!

Poloidal transit distance







No need for poloidal injection speed

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Conclusion

Dust size, injection speed and direction determine its fate

Large vertical injection speed → destruction

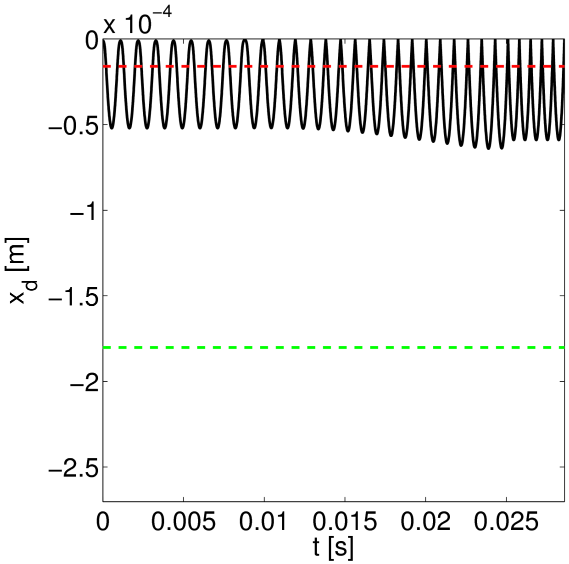
Large poloidal injection speed → increases survivability

	Small injection speed	Critical poloidal injection speed for survivability (L/τ_{melt})
Small particles: r_d~0.1 μm	Redeposits locally	6500 m/s
Medium particles: r_d~1 μm	Redeposits non-locally: mass migration	370 m/s
Large particles: r_d~10 μm	Can survive: PMI loss	0 m/s

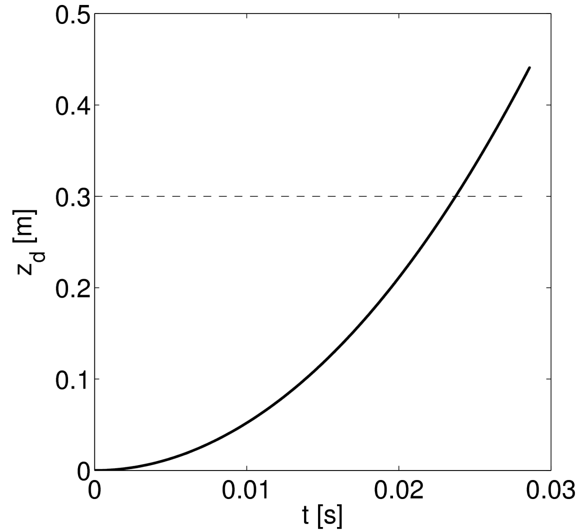
Needs to be complemented (i.e. generation rate vs dust size) by the material science perspective!

Can we use dust for something useful? Maybe

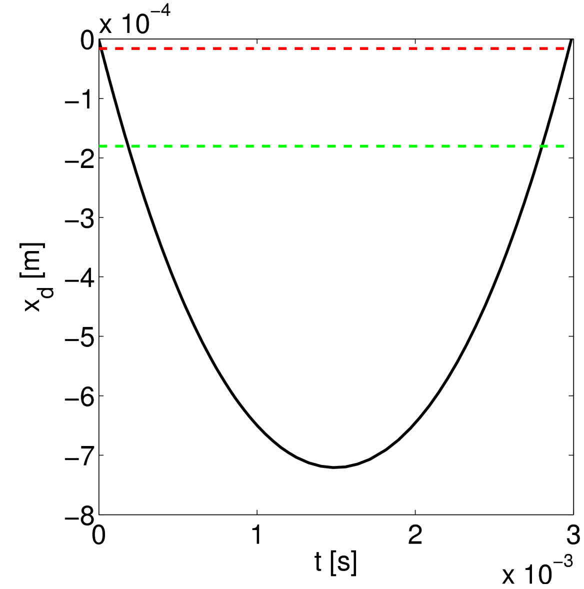
- Let's reconsider the previous results for 10 μm dust
- Dust can travel the divertor poloidally without melting



Poloidal transit distance



Trajectory of a dust grain injected with v_x=1 m/s

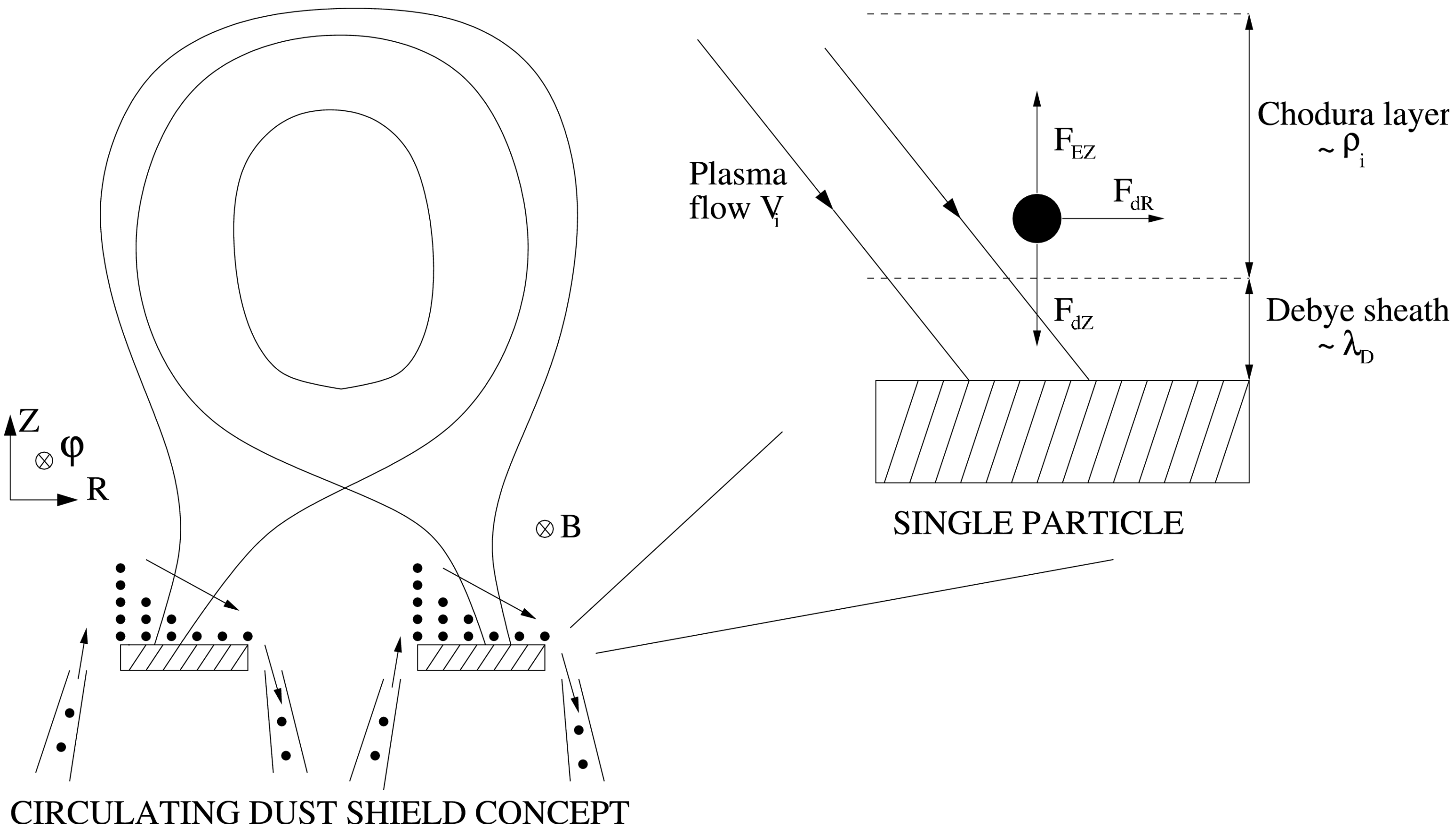


T_{fin}~3200 K

$V_{pol,inj}$~100 m/s

Dust divertor shield

- Tang, Delzanno, J. Fus. En. (2010)



Sheath energy fluxes profiles

$$\theta = 10^\circ$$